BIOCOMPATIBILITY AND MECHANICAL BEHAVIOUR OF ADVANCED MATERIALS FOR BONE IMPLANTATION

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SYNOPSIS

1. INTRODUCTION

Bone tissue engineering has emerged as a vital interdisciplinary field that seeks to replace or regenerate damaged bone through biomimetic materials. Among the various materials explored for bone regeneration, bioactive glasses have garnered attention due to their excellent osteoconductivity, biodegradability, and ability to bond chemically with bone. The most studied glass systems include 45S5 Bioglass and its derivatives; however, the 1393 and 1393B3 glass systems have emerged as promising alternatives due to their superior mechanical properties and faster degradation rates.

Despite their potential, challenges persist regarding the mechanical robustness, controlled degradation, and biological integration of these materials. To address these limitations, researchers have focused on modifying bioactive glasses with rare earth elements (REEs) such as cerium (Ce), lanthanum (La), and cobalt (Co) to tailor their structural and biological properties. This thesis investigates the synthesis, characterization, and evaluation of Ce-La co-doped 1393 glasses and CoO-doped borate-based 1393B3 scaffolds, aiming to enhance their performance in bone regeneration applications.

2. LITERATURE REVIEW

Bioactive glasses have evolved from the pioneering 45S5 glass to more complex systems like 1393 and 1393B3, which show improved mechanical properties and degradation profiles. The incorporation of REEs has shown promise in enhancing the network connectivity and functional properties of these glasses.

2.1 1393 and 1393B3 Glasses 1393 glass is a silicate-based composition with components such as SiO_2, CaO, Na_2O, P_2O_5, K_2O, and MgO. Its borate-modified variant, 1393B3, replaces a portion of the silica network with borate, leading to faster degradation and improved ion release profiles. The cotton candy form (1393B3) offers high porosity suitable for tissue ingrowth.

2.2 Role of Rare Earth Elements (REEs) REEs like Ce and La provide antioxidant properties, enhance proliferation, and influence osteogenic differentiation. Ce^{4+} ions are known for scavenging reactive oxygen species (ROS), thus promoting cellular activities. La^{3+} enhances the mechanical strength and modulates cell interactions. Co^{2+}, on the other hand, has been shown to improve angiogenesis, making it favorable for vascularized tissue regeneration.

2.3 Challenges in Bioactive Glass Development Despite promising in vitro results, clinical translation is limited due to poor mechanical strength, uncontrolled degradation rates, and inadequate biological integration. REE doping offers a pathway to overcome these limitations by fine-tuning glass network properties.

3. STATEMENT OF THE PROBLEM

Though 1393 and 1393B3 glasses exhibit favorable characteristics for bone repair, several challenges limit their efficacy:

- Brittle nature and low mechanical strength
- Rapid or uncontrolled degradation in physiological environments
- Insufficient tribological properties for load-bearing applications
- Poor long-term biointegration

This research aims to enhance the structural and mechanical behaviour of 1393 and 1393B3 bioactive glasses by incorporating Ce, La, and Co through melt-quenching and sol-gel methods, followed by comprehensive characterization and biological evaluation.

4. OBJECTIVES OF THE STUDY

- ✓ To synthesize CeO_2-La_2O_3 co-doped 1393 bioactive glasses and CoO-doped borate-based 1393B3 scaffolds.
- ✓ To fabricate porous scaffolds using foam replication and sol-gel techniques.
- ✓ To evaluate structural, mechanical, and morphological properties using XRD, FTIR, SEM, TEM, and mechanical testing.
- ✓ To assess in vitro bioactivity through simulated body fluid (SBF) studies.
- ✓ To evaluate cytocompatibility using in vitro cell culture and MTT assays.
- ✓ To validate bone regeneration potential through in vivo studies using animal models.

5. MATERIALS AND METHODS

5.1 Materials

- Reagents: Analytical-grade precursors such as SiO_2, $CaCO_3$, Na_2CO_3, H_3BO_3, P_2O_5, La_2O_3, CeO_2, CoO
- Simulated Body Fluid (SBF) components prepared as per Kokubo protocol
- Cell lines: MC3T3-E1 or similar osteoblast-like cells for biological evaluation

WEIGHING & MIXING
MELTING IN A FURNACE AT 1400±5 °C
ANNEALING
CUTTING FOR DESIRED PIECE
GRINDING & POLISHING
NOW SAMPLES READY FOR FURTHER TEST

Figure 1Flow chart of Bioglass samples prepared by the glass melting route

5.2 Methods

5.2.1 Synthesis of Glasses

- **Melt-quenching**: Batch mixing, calcination, melting at 1450°C, quenching in steel plates, and grinding
- **Sol-gel**: Hydrolysis and condensation of precursors followed by drying and calcination

5.2.2 Scaffold Fabrication

- **Foam replication**: Polyurethane foam as template dipped in slurry and sintered
- **Pelletization**: Compaction of glass powders into cylindrical discs for testing

5.2.3 Characterization

- **XRD** for phase analysis
- **FTIR** for bonding information
- **SEM & EDAX** for morphology and elemental distribution

- **TEM** for internal nanostructure visualization
- **Mechanical testing**: Flexural strength, compressive strength, microhardness

5.2.4 Biological Studies

- **In vitro**: SBF immersion for apatite formation, cell culture for viability and proliferation
- **In vivo**: Implantation in rabbit/bone defect models, followed by histological and radiological assessments

6. RESULTS AND DISCUSSION

6.1 Ce-La Co-Doped Glasses

- Glasses remained amorphous with enhanced structural stability
- FTIR revealed stronger Si-O-Si and P-O bonds
- Improved density and microhardness values
- Apatite layer formation confirmed in SBF within 7 days
- pH remained within biocompatible limits

6.2 TEM Analysis

- TEM showed nanocrystalline inclusions within amorphous matrices
- Crack deflection mechanisms evident, suggesting improved fracture toughness

6.3 La_2O_3-Modified Fluoroaluminosilicate Glass

- High chemical durability and increased mechanical strength
- Fluoride incorporation contributed to higher network connectivity

6.4 CoO-Doped Borate Glass Scaffolds

- Enhanced porosity and uniform pore size distribution
- Higher compressive strength than undoped borate glasses
- SEM showed well-formed apatite and favorable morphology
- In vitro studies showed higher osteoblast viability and proliferation

7. IN VIVO STUDIES

Animal studies confirmed successful integration of scaffolds into bone defects. Radiological assessments showed faster healing in REE-doped groups. Histological analysis confirmed new bone formation, vascularization, and minimal inflammatory response.

8. CONCLUSION

The incorporation of rare earth oxides into 1393 and 1393B3 glass matrices significantly enhances their structural, mechanical, and biological properties. The Ce-La combination improved both the mechanical strength and biocompatibility, while CoO doping in borate glasses imparted excellent degradation control and osteogenic potential. These findings present a promising pathway for the development of next-generation bioactive scaffolds suitable for orthopedic and dental applications.

9. FUTURE SCOPE

- Optimization of scaffold architectures using 3D printing
- Exploration of additional REEs like Yb, Gd, and Sm
- Long-term animal trials and clinical validation
- Functionalization with growth factors or antibiotics
- Development of composite systems integrating polymers and ceramics

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